C. Intermediate-Rate Crush Response of Crash Energy Management Structures

Co-Principal Investigator: Raymond G. Boeman
Oak Ridge National Laboratory
53-1/2 W. Huron St., Suite 213
Pontiac, MI 48342
(248) 452-0336; fax: (248) 452-8992; e-mail: boemanrg@ornl.gov

Co-Principal Investigator: J. Michael Starbuck
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-8048
(865) 576-3633; fax: (865)-574-8257; e-mail: starbuckjm@ornl.gov

Project Manager, Composites: C. David Warren
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-6065
(865) 574-9693; fax: (865) 576-4963; e-mail: warrencd@ornl.gov

Technology Area Development Manager: Joseph A. Carpenter
(202) 586-1022; fax: (202) 586-1600; e-mail: joseph.carpenter@ee.doe.gov
Field Technical Manager: Philip S. Sklad
(865) 574-5069; fax: (865) 576-4963; e-mail: skladps@ornl.gov

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Objective

- Develop unique characterization facility for controlled progressive crush experiments, at intermediate rates, of automotive materials (polymer composites, high-strength steels, aluminum) and structures.
- Study the deformation and failure mechanisms of automotive materials subjected to crush forces as a function of impact velocity.
- Obtain specific energy absorption and strain data, and correlate with deformation and failure mechanisms to describe the unknown transitional effects from quasi-static to high loading rates for polymer composites.
- Characterize the strain rate effects for metallic materials and components.
- Provide access to unique test capability to university, industry, and government users for collaborative research.

Approach

- Develop a unique high-force (270-kN), high-velocity (8 m/s) servo-hydraulic machine to conduct progressive crush experiments on structural components at intermediate rates.
- Use high-speed imaging to observe and document deformation and damage mechanism during the crush event.

- Conduct strain measurements at discrete locations and explore full-field measurements of strains and curvatures.
- Coordinate polymer composites investigations with the Automotive Composites Consortium (ACC) Energy Management Group.
- Coordinate steel investigations with the Auto/Steel Partnership.

Accomplishments

- Completed design modification and fabrication to achieve increased performance (125%) up to 8 m/s.
- Completed installation and initial operator training at the National Transportation Research Center (NTRC).
- Completed new acceptance tests on-site to demonstrate enhanced performance.
- Completed design and fabrication of test fixtures for testing five different tube geometries.
- Completed integration of high-speed data acquisition with test operation.
- Completed vendor demonstrations on four high-speed video systems.
- Completed a total of 38 shakedown tests as part of high-speed video assessments, capability demonstrations, and machine commissioning.
- Held official dedication ceremony in August 2003.

Future Direction

- Procure high-speed video.
- Explore techniques for full-field measurements of strains and curvatures.
- Develop User Interaction Plan.
- Support user collaboration as required.

Introduction

Progressive crush is an important mechanism by which the kinetic energy of a traveling automobile is dissipated in a collision to protect the safety of occupants. Unfortunately, the mechanisms governing the progressive crush response of some emerging automotive materials are not well understood. Additionally, many of these materials are known to exhibit responses that are sensitive to rate of loading.

Understanding the influence of impact velocity on the crush response of materials and structures is critically important for crashworthiness modeling inasmuch as collisions occur at a range of velocities. Additionally, from a structural standpoint, the deformation (or strain) rate is generally not unique from either a spatial or temporal standpoint. Consequently, it is important to quantify the behavior of materials at various strain rates.

Test Machine for Automotive Crashworthiness (TMAC)

Typically standard test machines are employed for experiments at quasi-static rates whereas drop towers or impact sleds are the convention for dynamic rates. These two approaches bound a regime within which data, for experiments at constant impact velocity, are not available by conventional experimental practice. This regime is termed herein the intermediate-rate regime and is defined by impact velocities ranging from 1 m/s to 5 m/s. Investigation of rate effects within this regime requires experimental equipment that can supply a large force with constant velocity within these rates. Using a drop tower or sled at intermediate rates, although technically possible, is problematic due to the prohibitively large mass required to maintain constant velocity during the crush. Consequently, the Oak Ridge National Laboratory (ORNL) and the Automotive Composites Consortium (ACC) collaborated to define specifications for a unique experimental apparatus that mitigates the shortcomings of existing equipment. MTS Systems Corporation designed and built the servo-hydraulic test machine, referred to as the TMAC. As shown in Figure 1, TMAC is uniquely capable of conducting controlled progressive crush tests at constant velocity in the intermediate velocity range (i.e., less than 5m/s) owing to the large energy available at those rates and to the sophisticated simulation and control software that permits velocity uniformity to within 10%.

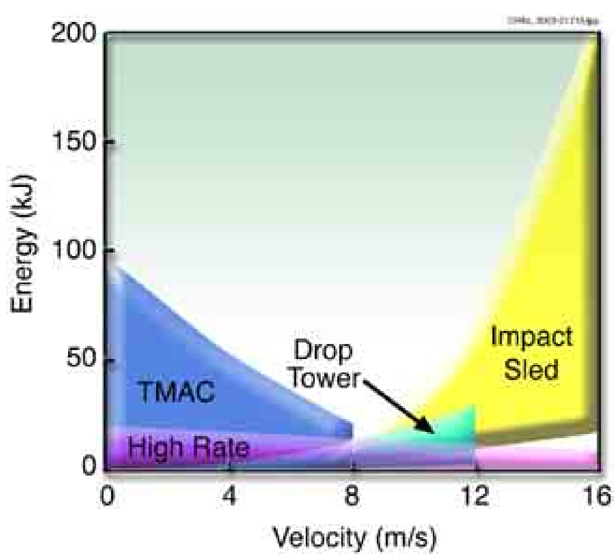

Figure 1. Energy plot indicating TMAC's unique capability of supplying enough energy at the intermediate rates for controlled, constant-velocity crush tests.

The new experimental facility will be used to understand the crush behavior between the static and dynamic (8-m/s) conditions.

Status

Since the last reporting period, the machine was disassembled at the vendor's location (MTS Systems Corp., Eden Prairie, MN) for shipment to the NTRC. A delay of approximately 1 month was encountered due to the replacement of a leaking actuator seal. The machine arrived for installation at NTRC in late October 2002. MTS personnel were on site for approximately 2 weeks for the installation, which was completed on November 1 (see Figure 2). The acceptance tests were executed again at NTRC to verify that the performance was not altered during the shipment process (see Figure 3). The machine met or surpassed the enhanced specifications including:

- No-load velocity of 8 m/s constant to within 10% over 115 mm.
- Sustained crush force of 133 kN at 6 m/s constant to within 10% over 115 mm.
- Sustained crush force of 267 kN at 4 m/s constant to within 10% over 115 mm.

Limited training was provided by MTS, but training videos and brief documentation in the form of PowerPoint presentations were provided. The vendor training videos that describe the detail procedures for simulation and iteration—for obtaining constant velocity—were not received until the end of February which delayed extensive use of the machine.

Meanwhile, mounting fixtures for 3-in. circular steel tubes, 4-in square composite tubes, 2- by 4-in rectangular tubes and 2-in square tubes were designed and fabricated. The designs incorporate a quick change out feature to expedite testing as opposed to the potting (bonding) approach that is common to drop tower and impact sled testing. The 4-in. square fixture was manufactured first to validate the concept to permit modification

Figure 2. TMAC installation at NTRC.

Figure 3. Aluminum honeycomb specimen before and after crush during acceptance test demonstrating sustained crush force of 133 kN at a velocity of 6 m/s constant to within 10% over 115 mm.

as necessary (see Figures 4 and 5). A series of tests were run using the 4-in. square composite tubes provided by the ACC that demonstrated external clamping of the specimens was a valid concept. A typical failed

Figure 4. Square composite tube specimen in prototype fixture.

Figure 5. Square tube test fixture.

specimen is shown next to an untested specimen in Figure 6. An internal plug fixture was also designed and fabricated for testing the 4-in. square tubes, but this

Figure 6. Uncrushed and crushed polymer composite tubes (4-in. square cross-section).

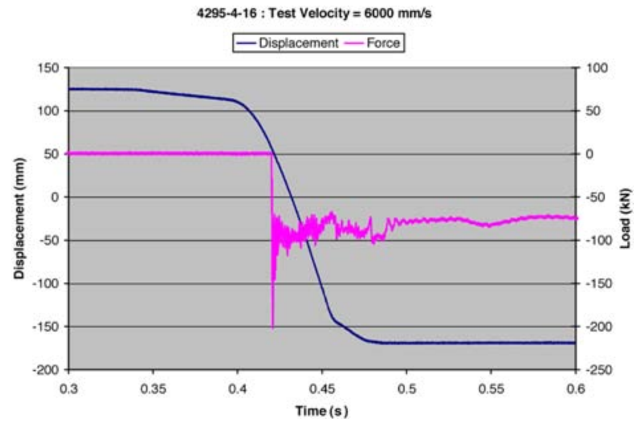

Figure 7. Typical load and displacement data for a 4-in. square carbon fiber composite tube tested at 6 m/s.

concept has not yet been evaluated. Fabrication has now been completed on various fixtures and supporting hardware that will enable testing of five different tube geometries. The fifth geometry that is not described above is a 4-in. circular tube.

A LabView program was developed to obtain the test data from two high-speed data acquisition (DAQ) modules—a 12-bit synchronous card with four channels, and a 16-bit asynchronous card with eight channels. The program synchronizes the data and is triggered from the TMAC control software that initiates the impact. One card has higher signal resolution at the expense of temporal resolution and synchronicity, while the other card sacrifices signal resolution for fast, synchronous measurements. The merits of the two cards are being assessed.

The functionality of the data system was demonstrated and will be refined and updated as future test requirements are defined, including the capability for recording strain gage signals. The current DAQ configuration reads one LVDT for displacement, a load cell and load washer for force, and two accelerometers. The accelerometers were chosen to provide 1-g/V sensitivity and 10-g/V sensitivity. Figure 7 shows a typical response of a 4-in. square composite tube tested at 6 m/s. The measured displacement from the LVDT is plotted on the left ordinate, and the measured force from the load washer is plotted on the right ordinate. The force trace is typical of a progressively crushed specimen with a distinct initial peak, followed by drop off in load to a relatively constant level for the remaining crush distance. A similar plot of a 3-in.-diam steel tube is shown in Figure 8. The steel tube, which progressively crushes by plastic hinge formation (see Figure 9), shows much fewer oscillations in the force data than the composite tube.

The accelerometer data are integrated to calculate the velocity, and this is being compared with the differentiated displacement data. Preliminary tests have shown that essentially the same velocity is calculated using the two different measurements, but issues related to signal noise and filtering need to be resolved. To illustrate this point, results from a 6-m/s test without a specimen are shown in Figure 10. There are three plots in this figure, the LVDT displacement data, the velocity calculated from the 10-g/V accelerometer, and the velocity calculated from the displacement using a 25-point moving average. Ultimately, data for force, displacement, time, acceleration, and strain will be acquired and synchronized with high-speed video for complete characterization of the event.

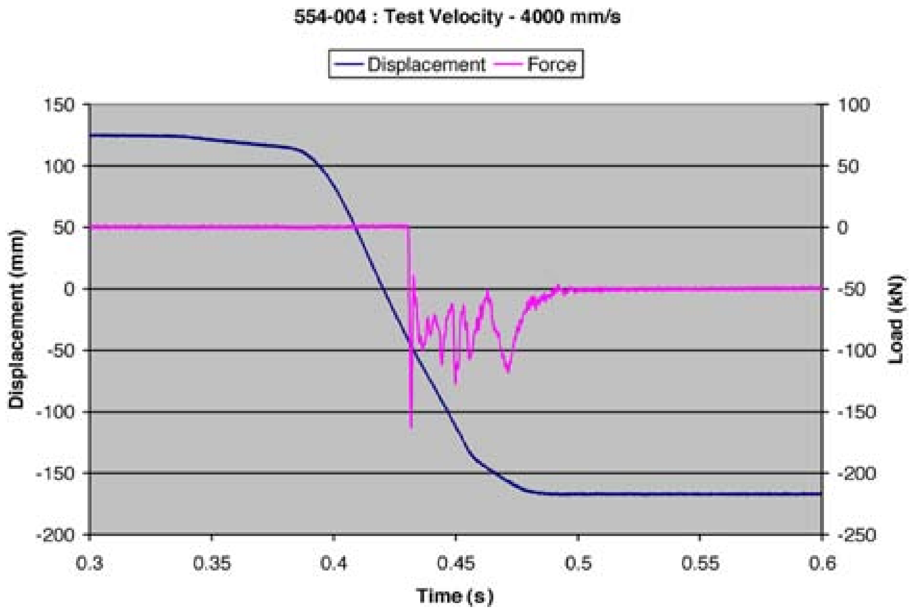

Figure 8. Typical load and displacement data for a 3-in. diam steel tube tested at 4 m/s.

Figure 9. Metallic tubes tested in TMAC demonstrate the conventional folding pattern associated with plastic hinge formation.

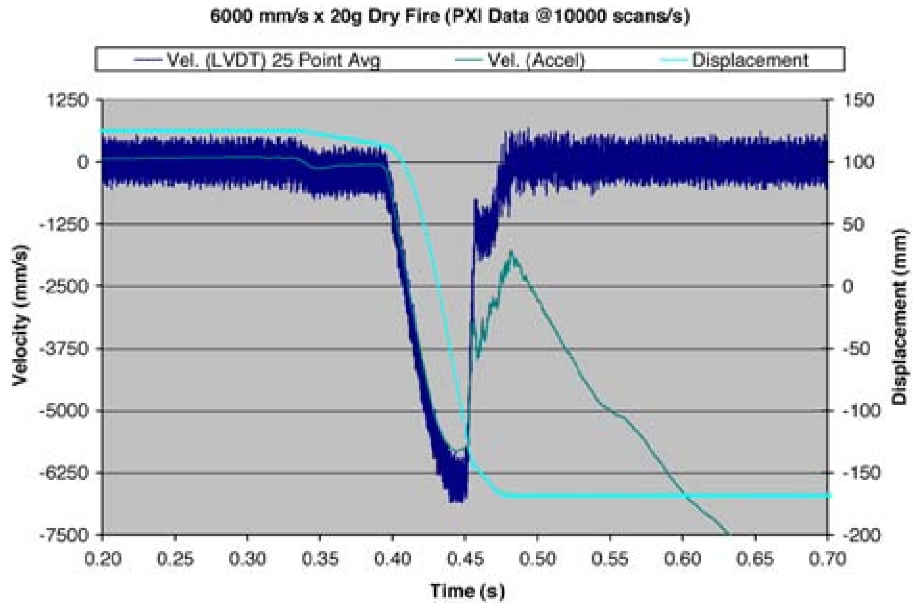

Figure 10. Calculated velocities from a 6-m/s test without a specimen.

The pressure accumulators were replaced with American Society of Mechanical Engineers (ASME) code-stamped versions per regulation, and an air abatement system to collect the carbon fiber dust cloud was implemented. The latter was required for health concerns as well as for improved imaging.

Five high-speed video vendors were contacted to identify suitable candidates for the imaging needs. Demonstrations of the three most promising systems were held at NTRC during the third week. Final selection of the video system was delayed to review the next-generation systems, which are expected to be released in the first quarter of FY 2004. The new systems offer a combination of increased resolution, decreased shutter speed, and greater light sensitivity at essentially the same cost.

A dedication ceremony was held in August, which marked the official commissioning of the capability. A total of 38 experiments have been conducted as part of shakedown experiments, high-speed video assessments, capability demonstrations, and machine commissioning.

Conclusions

TMAC has passed and exceeded the performance specifications as demonstrated by acceptance tests conducted at both the vendor site and after installation at NTRC. It provides a unique capability to measure the specific energy absorption on crush tubes as a function of (constant) impact velocity within a range from quasi-static to 8 m/s.

Progress in conducting experiments has been delayed due to replacement of pressure accumulators and the learning curve associated with the software operation to optimize machine parameters for constant velocity tests. Conducting the physical test is more complex than typical test operations, but sufficient expertise has been developed to render it rather routine. However, conducting the virtual test to determine the precise machine parameters to provide constant velocity is quite complex. The full documentation describing the multiple steps in the software was not received from the vendor until February 2003, which resulted in delays in developing the requisite expertise. Sufficient experience to conduct constant velocity tests for a general specimen behavior is expected by the end of the first quarter FY 2004.

Additional work is required to refine the data acquisition, particularly with regard to comparisons of the two data acquisition cards, filtering of data, and determination of velocity from accelerometer signals.